ARMY RESEARCH LABORATORY

Analysis of Long Rods Impacting Ceramic Targets at High Velocity

by Fred I. Grace
and Nevin L. Rupert

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Abstract

This paper presents an analysis of recently reported experimental data on penetration of semi-infinite ceramic and metal targets by long rods at relatively high velocity (up to 4,500 m/s). Data examined were for pure tungsten rods having length-to-diameter ratios of 15 and 20. The rods were impacted by confined aluminum nitride (A1N), alumina ($A1_2O_3$), and a metal target of aluminum in reverse ballistic tests. Penetration rates were reported to be essentially constant throughout the penetration process at all impact velocities considered. Further, depths of penetration characterized as "primary penetration" agreed with expected levels based on measured penetration rates and rod erosion rates. However, above an impact velocity of about 2,000 m/s, considerably more penetration was observed in A1N and aluminum targets. In this effort, established techniques were used to treat penetration into semi-infinite ceramic, to include the high initial strength of the ceramic and its degradation, in time, through time-dependent damage mechanisms. The model results agreed with reported primary penetrations for A1N and aluminum targets. Further, additional "secondary penetration" by the rod erosion products at these high impact velocities was explored. This report includes detailed descriptions of the analysis and some physical interpretations for the observations. This research was based on U.S. Government-sponsored work and open literature sources.

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1. INTRODUCTION

Depth-of-penetration (DOP) tests are often used to evaluate candidate ceramic materials as armor materials and to study efficiencies of long-rod penetrators against those types of targets. Such targets can consist of semi-infinite ceramic or configurations of layered ceramic backed by semi-infinite steel. For semi-infinite ceramic, no backing material is required, since the ceramic thickness is chosen to exceed the penetration ability of the rod. DOP test results for the layered targets using a rod impact velocity of 1,500 m/s have been obtained by Woosley, Mariano, and Kokidko [1] for aluminum oxide (Al_2O_3), aluminum nitride (AlN), and titanium diboride (TiB_2), while Rupert and Grace [2] also investigated TiB_2. Data for higher velocity impacts to 3,037 m/s using high-density rods vs. Al_2O_3 have been reported by Hohler, Stilp, and Weber [3]. Orphal et al. [4] and Subramanian and Bless [5] reported systematic sets of penetration data for semi-infinite ceramic targets of AlN and Al_2O_3 for impact velocities up to 4,500 m/s.

While there is a growing DOP database, the multilayered targets present complications in analysis since multiple interfaces of different materials and shock (pressure) reflections at interfaces need to be taken into account. It is of interest to examine penetration processes in the more ideal semi-infinite ceramic to explore time-dependent damage mechanisms more fully, particularly in the context of a penetration model, and assess strength effects and damage growth-rate coefficients, for example. The purpose of the present effort is to analyze the experimental results of Orphal et al. [4] and Subramanian and Bless [5] to develop an analysis describing penetration into ceramic targets throughout a wide range of impact velocities.

The approach utilizes the analyses of Grace [6,7] for basic penetration and Grace and Rupert [8] for penetration into ceramics. In the cited work, the authors included a time-dependent damage mechanism for the ceramic response to ballistic impact and calculated DOP test results for Al_2O_3 at 1,500 m/s. Within the penetration analysis, models of Curran et al. [9] and Cortez et al. [10] were used to describe both initial intact and fully damaged (comminuted) states of ceramic materials. Implementation into the penetration model provided a conditionally determined local strength for ceramic material as penetration proceeds into the target.

Progression of damage within the stressed material under rod impact [8] was considered to occur within "process zones" as defined by Pabst, Steeb, and Claussen [11]. For purposes of penetration modeling, damage zones are defined to extend from the penetrator nose to a forward boundary of crack fronts. Propagation rates for crack fronts were taken to be close to the Rayleigh surface wave velocity as suggested by McClintock and Argon [12]. Propagation of process zones and resulting material degradation as modeled [8], in a simplified way, were consistent with the highly structured wave code computer calculations of Curran et al. [9]. The essentials of this report are to be published in the open literature (Grace and Rupert [13]).

2. STATEMENT OF THE PROBLEM

There were three essential results reported by Orphal et al. [4] with regard to penetration into semi-infinite ceramic material of AlN by a pure tungsten rod. The first result is that penetration rates were measured by flash x-rays to be essentially constant throughout the penetration process and significantly below rates for hydrodynamic penetration. This result was also reported by Subramanian and Bless [5] for similar rods against semi-infinite Al_2O_3 targets. A typical result is shown in Figure 1. Lower penetration rates cannot be rationalized on the basis of density changes in the ceramic, since there is no evidence that its density could increase at any reasonable distance from the rod-target interface. Thus, it is assumed that lower penetration velocities are due to ceramic strength. The constant penetration rate being lower rules out hydrodynamic penetration, even though constant velocity penetration is one of its characteristics. Further, the theory of rod penetration indicates that penetration into metals of relatively high strength, for example, is a nonsteady process and the penetration rate is reduced in time, since the metal target maintains a constant strength. Thus, a preliminary conclusion is that penetration into ceramic is characterized by a process whereby strength is reduced in time and, consequently, with distance into the ceramic.

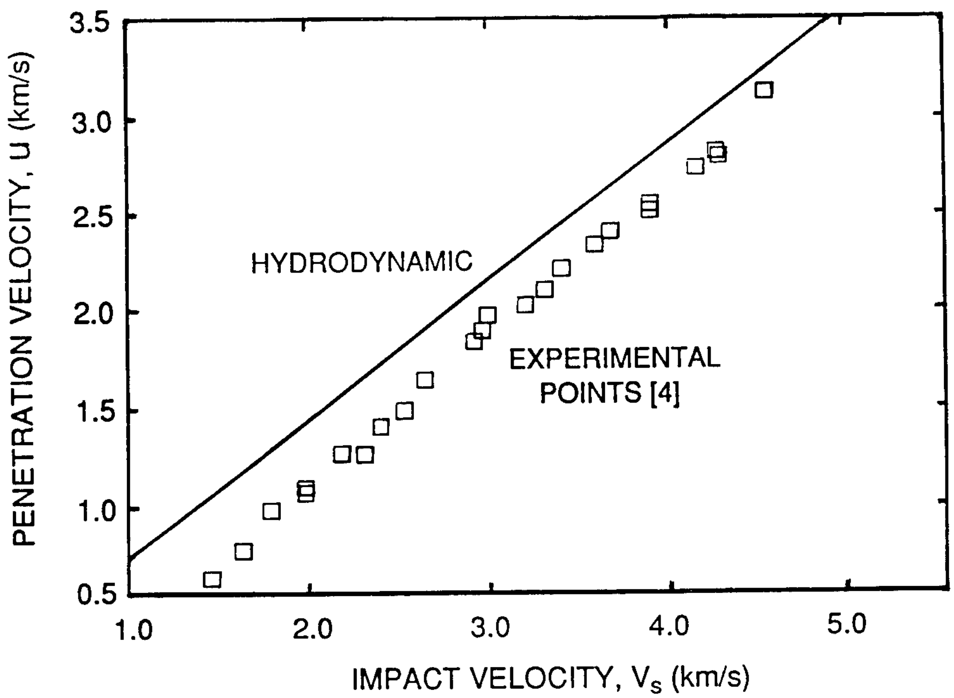

Figure 1. Penetration rates for aluminum nitride [4].

The second result of Orphal et al. [4], also supported by Subramanian and Bless [5], is that expected penetration depths into semi-infinite ceramic can be determined from measured penetration rates and rod erosion (consumption) rates. This contribution was characterized as "primary penetration" and was facilitated by the penetration rate being constant. In both cases, a direct measurement of total penetration indicated that primary penetration represents the total through a velocity range up to 2,000 m/s.

The third result of Orphal et al. [4] is that total penetration depths into ceramic for pure tungsten rod-AlN target combinations can exceed the primary penetration, and this occurs only above an impact velocity of 2,000 m/s. This additional penetration also appears in the work of Orphal [14] for pure tungsten rods penetrating silicon carbide (SiC) and boron carbide (B_4C). The total penetration was found to increase with impact velocity and to exceed primary penetration by as much as 30%. Beyond 4,000 m/s, total penetration exceeded the hydrodynamic limit. In contrast, Subramanian and Bless [5] found that any additional penetration beyond the

primary had to be small in the Al_2O_3 target, although in their work, the maximum impact velocity used was not as high (3,400 m/s).

Initial calculations conducted in the current work, which included a time-dependent strength loss mechanism, produced a near constant penetration velocity close to measured values and also gave results in agreement with primary penetrations for AlN targets. Further, an analysis of similar data provided by Subramanian et al. [15] for pure tungsten rods impacted by metal targets of aluminum also gave results consistent with primary penetration. Thus, it was concluded that the additional penetration could not be explained only by a loss of ceramic strength during the penetration process. As a result, the following mechanisms were examined to explain the additional penetration:

• Rigid-body penetration: In general, rigid-body penetration is not observed at the end of eroding-body penetration in targets of high strength at impacts above 2,000 m/s, since the penetrator has been reduced in length, mass, and velocity to a large extent. For ceramics whose strength has been degraded substantially, as in the present case, rigid-body penetration is still not likely, since the magnitude of primary penetration can only be obtained by nearly total rod consumption. Further, rigid-body penetration is dominated by penetrator mass and thus should be greatest at low-impact velocity, where unconsumed portions of the rod are the largest. Rod mass would decrease with increased impact velocity. The present eroding-body penetration calculations show that far too little residual penetrator mass remains for impacts above 2,000 m/s to provide any substantial contribution to penetration. Thus, rigid-body penetration is unlikely to be responsible for additional penetration in the ceramic material.

• Cavity expansion due to afterflow: The energetics of the afterflow can create an apparent additional amount of "penetration" depth. When the effect produces a near-spherical cavity, its radius depends upon the cube root of the energy required to form the cavity. Further, energy available for cavity expansion is likely to be proportional to the square of the impact velocity so that the cavity radius should depend upon impact velocity raised to the two-thirds power. In order for additional penetration due to cavity expansion not to be seen below 2,000 m/s, there

might have to be some critical threshold energy below which no expansion could take place. If the previous conditions were in place, then cavity expansion could follow the trend of the additional penetration. Orphal et al. [14] discusses this possibility.

- Penetration by rod erosion products: The combination of a high-density rod and low-density target material produces rod erosion products that can flow forward into the target, especially at high impact velocity. Preliminary estimates suggest that the flow switches from rearward (net flow out of the target) to forward flow at an impact velocity of about 850 m/s. Still, the forward velocity would be insufficiently high to produce penetration into the ceramic until the rod impact velocity reaches about 2,000 m/s. The calculations further show that the distribution of forward velocities within the erosion products is such that a slight length contraction takes place. While the integrity of erosion products in terms of a viable penetrator can be questioned, there have been reports by Gerlach [16] and Magness [17] that intact tubes can be formed from rod erosion products for stable materials, such as pure tungsten and a tungsten-tantalum alloy. If so, the penetrator formed by the erosion products could produce additional penetration that increases monotonically with impact velocity until it approaches its own penetration limit. The present work addresses this possibility.

The main focus of this analysis is to address <u>primary penetration</u> using the basic theory together with some approximations to model overall responses of ceramics. The possibility of additional <u>secondary penetration by rod erosion products</u> is also considered under ideal conditions.

3. ANALYSIS FOR PRIMARY PENETRATION

The penetration integral of Grace [6] for semi-infinite penetration is used as a starting point in the analysis. The theory treats an eroding and decelerating rod during impact with a plastically flowing target of semi-infinite thickness. Figure 2 describes the configuration of impact, wherein velocities of the rod, target material, and rod erosion products are defined relative to the

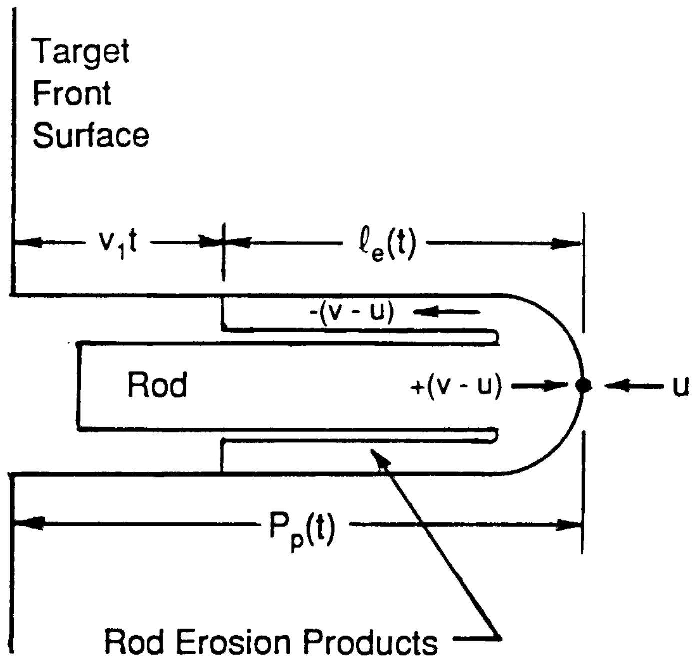

Figure 2. Rod/target impact conditions presented in the moving and laboratory reference frames.

rod-target interface which moves at a velocity u with respect to the laboratory reference system. Initial conditions are rod length ℓ_0, density ρ_p, rod striking velocity v_s in the laboratory frame, rod strength S_p, target density ρ_t, and target strength S_t. The integral for DOP P_s into a semi-infinite target is

$$P_s = - \int_{\ell_0}^{\ell} \frac{u(\ell)}{v(\ell) - u(\ell)} \, d\ell, \tag{1}$$

which differs from hydrodynamic penetration, since velocities for the rod tail v and penetration rate u are not constant but are functions of rod current length ℓ. Solutions to the integral depend upon specific forms for rod velocity $v(\ell)$, interface velocity $u(\ell)$, and initial penetration rate u_o. When the interface velocity does not vary much, as in quasi-steady processes, the difference between rod and interface velocities is

$$v(\ell) - u(\ell) = \left(v_s - u_0\right)\left[1 + \frac{2S_p}{\rho_p\left(v_s - u_0\right)^2} \ln\left(\frac{\ell}{\ell_0}\right)\right]^{\frac{1}{2}}. \tag{2}$$

For the case where the interface velocity is constant, $u(\ell) = u_0$, equation (2) is an exact solution for Tate's rod deceleration [18], as derived by Grace [7], relative to a coordinate system moving with velocity u_0. Equation (2) indicates that the velocity of the rod tail $v(\ell)$ will approach a constant value at high impact velocity. The $u(\ell)$ equation also allows for a nearly constant interface velocity at high impact velocity (through a consequent high value of u_0) and is

$$u(\ell) = u_0\left[1 + \frac{2S_t}{\rho_t u_0^2} \ln\left(\frac{\ell}{\ell_0}\right)\right]^{\frac{1}{2}}. \qquad (3)$$

The initial penetration rate u_0 is below the hydrodynamic value because of target strength primarily and has been given as

$$u_0 = \frac{v_s}{1+\gamma} - \frac{f(v_s)}{1+\gamma}\left[\sqrt{\frac{2S_t}{\rho_p}} - A\, g(v_s)\sqrt{\frac{2S_p}{\rho_t}}\right], \qquad (4)$$

where γ is the square root of the density ratio ρ_t/ρ_p and the hydrodynamic penetration rate $u_H = v_s/(1+\gamma)$. Also, $f(v_s)$ and $g(v_s)$ are functions which allow strength effects to diminish to zero as the impact velocity approaches the sound speed of the target material C_0, and $A = 1.1\,\gamma$ [6]. Solutions for the penetration depth of equation (1) are obtained numerically using equations (2) and (3) with rod length as the independent variable, while equation (4) determines u_0. From equation (2), the maximum rod consumption and resulting minimum rod length (final rod length ℓ_r) is determined when $v - u = 0$ as

$$\ell_r = \ell_0 \exp\left[-\frac{\rho_p}{2S_p}\left(v_s - u_0\right)^2\right], \qquad (5)$$

which shows that the residual rod has little length under the high rod impact velocities considered in this work. Further, dynamics of rod motion given by equation (2) show that, at high impact velocity, rod velocity is not expected to be reduced much until the very end of the penetration process. Thus, the approach used by previous investigators [4,5,14,15], based on a constant rod consumption rate to determine primary penetration, is a reasonable approximation to the rod deceleration process described previously at high impact velocity.

Penetration calculations depend upon strengths and densities of rod and target materials, as indicated. For metals, nominal values that reflect dynamic strengths and/or work-hardened states have been used with success [6,7]. In contrast, strength of ceramic materials, as noted by Curran et al. [9] and Cortez et al. [10], depends upon the amount of damage within the material. The current view is that the ceramic can be characterized by two states (i.e., intact and fully comminuted). Further, the strength τ_i of intact ceramic and the strength τ_c of the comminuted ceramic (due to friction) increase linearly with hydrostatic stress, respectively, according to

$$\tau_i = \tau_0 + b\sigma,\ \tau_c = \mu\sigma, \tag{6}$$

where τ_0 is an ambient strength, b is a strengthening coefficient, and μ is the coefficient of friction. Cortez et al. [10] explored the use of a damage fraction η to express the strength τ of partially damaged ceramic in terms of the two end states as

$$\tau = (1 - \eta)\,\tau_i + \eta\tau_c. \tag{7}$$

Grace and Rupert [8] developed a model to define the stress-time history during penetration by considering propagation of crack fronts (process zones) within the ceramic. Depicted in Figure 3 are two process zones, (a) and (b), of the earlier work. The physical model considers rod impact with the target front surface from which several wave fronts are propagated into the material. Process zone (a) is a manifestation of a subsequent shear wave that defines a region of crazing. Pabst, Steeb, and Claussen [11] define this process zone as a region of crack nucleation and subcritical, discontinuous crack extension. Crack fronts propagate at a rate related to the Rayleigh surface wave velocity [12]. Process zone (b) results from a very highly pressurized region of flow stagnation at the penetrator-target interface. The thickness of process zone (b) is taken to remain constant during penetration and to be on the order of a penetrator diameter d. Thus, the high-pressure region associated with zone (b) was defined to travel at the penetration rate $u(\ell)$.

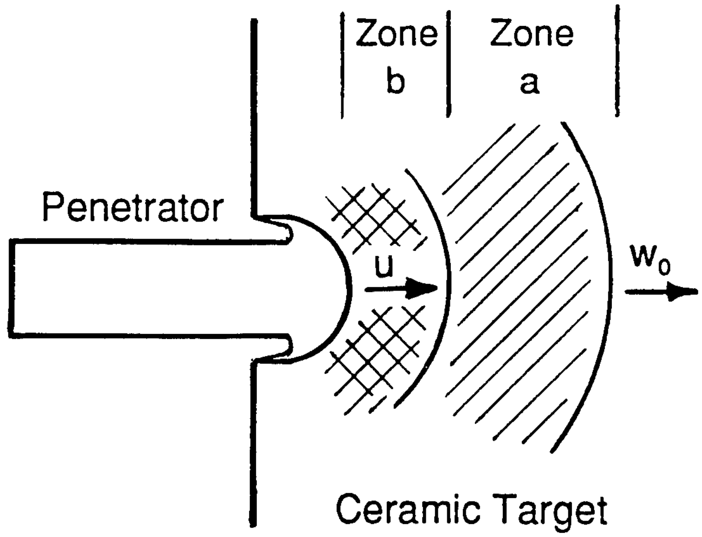

Figure 3. Definition of process zones used to describe damage regions behind (a) the propagating crack front boundary and (b) the high stress area directly in front of the penetrator.

Both process zones initiate simultaneously at the target front surface upon impact by the penetrator. The damage evolution, in terms of a rate at which the damage fraction evolves toward complete damage, was applied separately to each zone by Grace and Rupert [8] so that

$$\dot{\eta}_a = \dot{n}_{oa}\left(\sigma_a - \sigma_0\right),\ \dot{\eta}_b = \dot{n}_{ob}\,\sigma(t), \tag{8}$$

where motivation for evolution develops from an applied hydrostatic stress σ_a above some initial level σ_0 required for the onset of fracture in zone (a) and the Bernoulli stress history $\sigma = \sigma(t)$ associated with zone (b). In equation (8), $\dot{n}_{oa}$ and $\dot{\eta}_a$, and $\dot{n}_{ob}$ and $\dot{\eta}_b$, are the initial and subsequent time rates of change in the damage fraction in each zone, respectively, and t is time. The time available for each process zone to act on a point P depends on the time it takes for the rod-target interface to reach that point within the ceramic. By integrating the functions of equation (8) over time, and adding them, an expression for the cumulative damage is

$$\eta = \dot{n}_{oa}\left(\sigma_a - \sigma_0\right)\left[\frac{P-d}{u(\ell)} - \frac{P}{w_o}\right] + \frac{1}{4}\,\dot{n}_{ob}\,d\,\rho_t u(\ell)\,. \tag{9}$$

The damage functions of equation (9) combine with equation (7) to describe the shear strength and extent of damage within ceramic material. Maximum and minimum shear strengths possible for ceramics, based on the Griffith brittle fracture criterion [19], are $\tau_0 = \pm \sigma_{ult} / \sqrt{3}$, where σ_{ult} is either the ultimate strength of compression (maximum) or tension (minimum). When the damage fraction reaches a value of one, the material is fully comminuted. At that point, the normal stress responsible for friction is taken to be the Bernoulli pressure arising from target flow $u(\ell)$ so that target resistance to penetration is

$$S = R + \frac{1}{2} \mu \, \rho_t u(\ell)^2, \tag{10}$$

where R is a small minimum resistance of the comminuted material. Substituting equation (10) into equation (3) for S_t provides an approximate expression for $u(\ell)$ for fully comminuted ceramic material. Expanding that expression, neglecting R at high velocity, and retaining the first two terms lead to

$$u(\ell) = u_0 \left[1 + \mu \ln \left(\frac{\ell}{\ell_0} \right) \right]^{\frac{1}{2}}. \tag{11}$$

Equation (11) suggests that penetration rate in comminuted material may be controlled primarily by target resistance arising from friction. For lower ranges of high impact velocities considered here, $\mu < (2S_t/\rho_t)/u_0^2$. Thus, equation (11) produces a lower reduction in penetration rate with rod length loss than does equation (3) and $u(\ell)$ now represents an interface which more nearly approximates constant motion. However, at very high velocity, when u_0 is large, $\mu > (2S_t/\rho_t)/u_0^2$. This latter condition implies that penetration rates into a material with an initially high strength, but which transitions into granular material, may never reach hydrodynamic rates since $u(\ell) < u_0 < u_H$, always. Further, with lower penetration rates and consequent higher rod consumption rates, it is unlikely that penetration depths reach hydrodynamic levels before the rod is consumed. It is not clear, however, that the coefficient of friction for comminuted ceramic can be maintained at such high pressures. Certainly, for granulated metals, it is likely that melting and/or plastic flow of the granules would reduce friction substantially. In any event, equation (10) defines S_t in equation (4) as the effective strength to be used in the penetration analysis. The

damage fraction is computed continually, and S_t is adjusted appropriately during numerical integration of equation (1).

4. PENETRATION BY ROD EROSION PRODUCTS (REPs)

The possible secondary penetration by REP is explored on the basis of an idealized penetrator. It will be assumed that the primary penetration process is complete and that the REP must initiate penetration again at the bottom of the cavity with no interference by any residual rod mass. Further, it will be assumed that the final state of the target at the end of primary penetration will be the initial condition for secondary penetration by REP. Thus, REP will begin penetration into previously damaged ceramic material whose strength has been estimated. The expressions of the previous section are used also for REP penetration calculations. The REP is formed during the course of primary penetration with length and velocity as defined in Figure 2. Accordingly, REP velocity v_M with respect to the moving system and its velocity v_L in the laboratory reference frame, respectively, is

$$v_M(\ell) = \left[v(\ell) - u(\ell)\right],\ v_L(\ell) = -v(\ell) + 2u(\ell). \tag{12}$$

Since there can be a velocity gradient in the REP due to deceleration of the initial rod, a momentum-weighted average velocity v_e is assumed for the initial REP velocity. Thus,

$$v_e = \sum_i \ell_i\ v_i(\ell) / \sum_i \ell_i\ , \tag{13}$$

where ℓ_i and $v_i(\ell)$ are the increments of REP length and velocity $v_L(\ell)$ as determined during numerical integration for primary penetration. The REP's length ℓ_e at the end of primary penetration is

$$\ell_e = P_p - v_1 t_p, \tag{14}$$

where P_p is the total depth of primary penetration, t_p is the total time of primary penetration, and v_1 is the velocity of the first REP element.

Although the REP is created with near tubular form, it is treated in the ideal case as a legitimate rod of length ℓ_e and velocity v_e being able to support eroding-body penetration in the same sense as the initial rod. Estimates of its penetration for possible degraded states could be implemented using the present analysis through reductions in density and strength. Since possible degraded states have not been characterized in any quantitative sense, the case considered here was full strength and density of the initial rod as an upperbound for the REP material.

5. DISCUSSION OF CALCULATED RESULTS

5.1 Primary Penetration. The previous models were utilized to calculate penetration of pure tungsten long-rod penetrators into AlN, Al_2O_3, and aluminum targets. The basic material properties assumed for the penetrator and targets, as modeled, are provided in Table 1. Strengths shown for ceramics are values assigned to intact states.

Table 1. Material Properties Used in the Calculations

Material	Density (g/cm^3)	Strength (GPa)	C_o (m/s)
Al(6061-T6)	2.74	0.60	6,300
AlN	3.25	2.80	10,700
Al_2O_3	3.89	3.23	10,700
Pure W	19.3	1.10	—

Model coefficients used in the calculations for the time-dependent damage mechanism are listed here. These coefficients include $\dot{n}_{oa} = 5*10^{-4}\ Pa^{-1}\ s^{-1}$ [10], $\dot{n}_{ob} = 5*10^{-6}\ Pa^{-1}\ s^{-1}$ [8], $\sigma_0 = 100$ MPa [10], $\sigma_a = 200$ MPa [10], $w_0 = 6{,}000$ m/s [12], $b = 0.10$ [10], and $\mu = 0.145$ [9].

The minimum (cutoff) stress was adjusted to R = 200 MPa so that calculated primary penetrations matched the data for AlN. Nominal rod and target lengths associated with the data were 15.2 mm and 50.8 mm, respectively [4]. Calculated damage fractions and penetration rates for semi-infinite AlN targets at impact velocities of 2,000 and 4,000 m/s by rods of 15.2-mm length are given in Figure 4.

The particular damage growth rates used cause the ceramic material to transition to a fully comminuted state during the first quarter of penetration. Thus, target strength is reduced to that determined by frictional forces. The cutoff stress R causes termination in the penetration rate curves. Also, rod velocity and penetration rate vary slightly with time over much of the penetration. A very rapid change takes place only for a small and negligible time at the very end of the penetration process. For these particular calculations, measured penetration rates taken from Orphal et al. [4] were 1,050 m/s and 2,430 m/s, respectively. In the first case, calculations

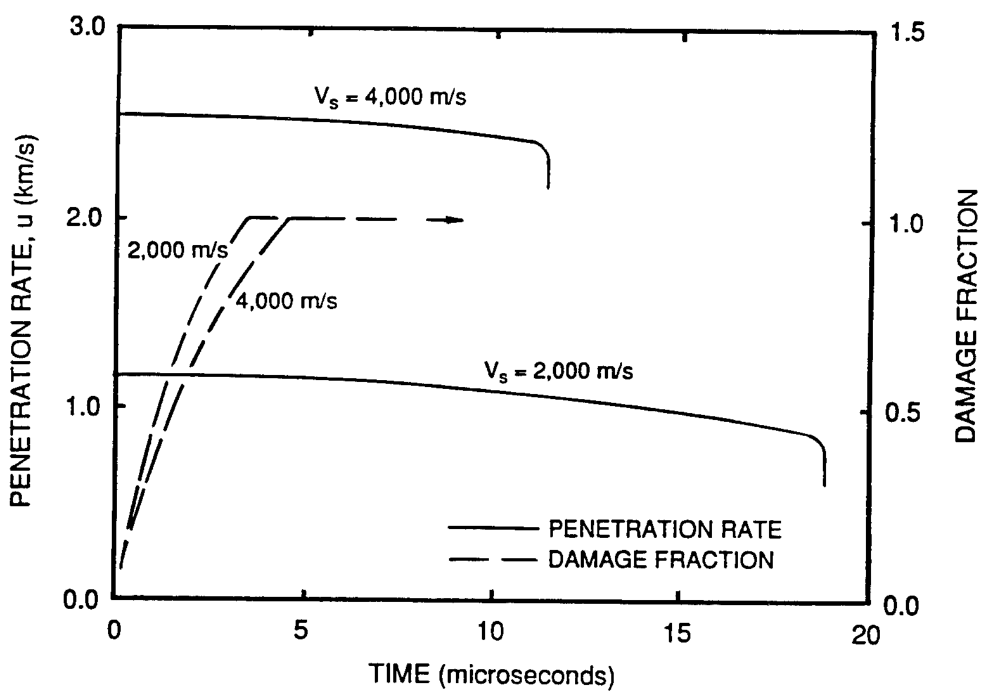

Figure 4. Calculated velocity-time and damage fraction-time plots for A1N for initial rod impact velocities of (a) 2,000 m/s and (b) 4,000 m/s.

varied from about 1,085 m/s initially to 900 m/s just before the rapid dropoff. At higher impact velocity, calculated penetration rates were from 2,550 m/s initially to 2,450 m/s.

In Figure 5, primary penetrations for the AlN target are compared with experimental data taken from Orphal et al. [4]. A good agreement can be seen over the entire range of impact velocity, which is essentially due to strength reductions during penetration. For example, when intact strength was used in the calculation at 2,000 m/s without the damage function, the calculations gave a P/L of only 0.561 as compared with 1.25. Also, calculations and data suggest that primary penetration may not increase much beyond an impact velocity of 3,800 m/s.

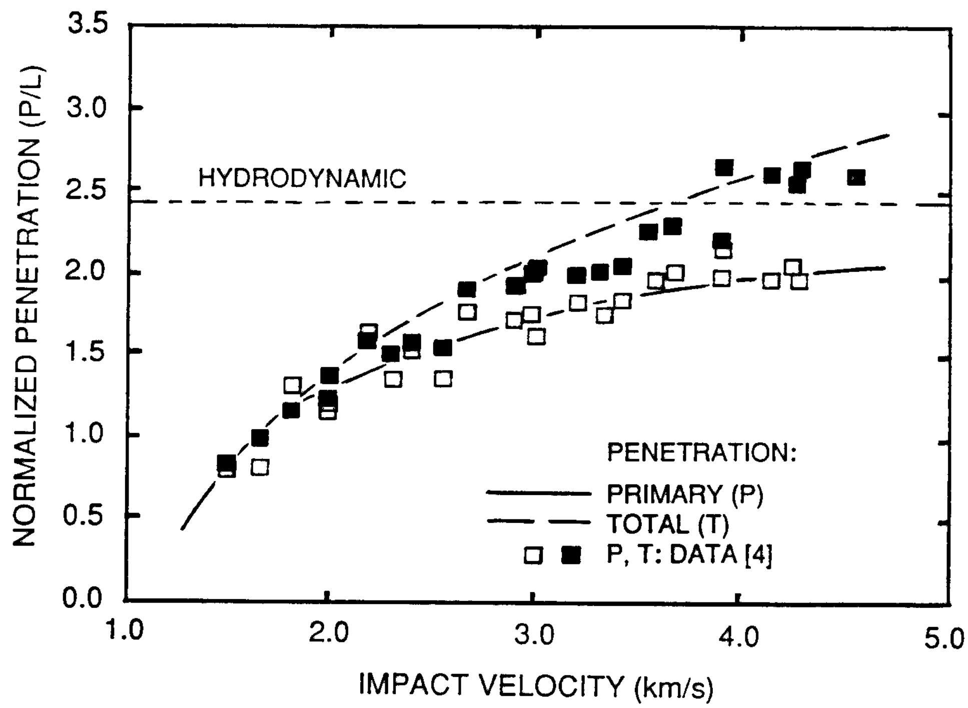

Figure 5. Calculated and experimental primary and total penetration in AlN.

Results for the Al_2O_3 target are shown in Figure 6. Below an impact velocity of about 2,500 m/s, calculations for primary penetration are somewhat above the mean of the penetration data, while beyond that velocity, the calculations are somewhat below the mean penetration. It should be noted that the primary penetrations of Subramanian and Bless [5] were reported to be essentially equal to the measured total penetration. Thus, experimental results for AlN and Al_2O_3 ceramics are qualitatively different.

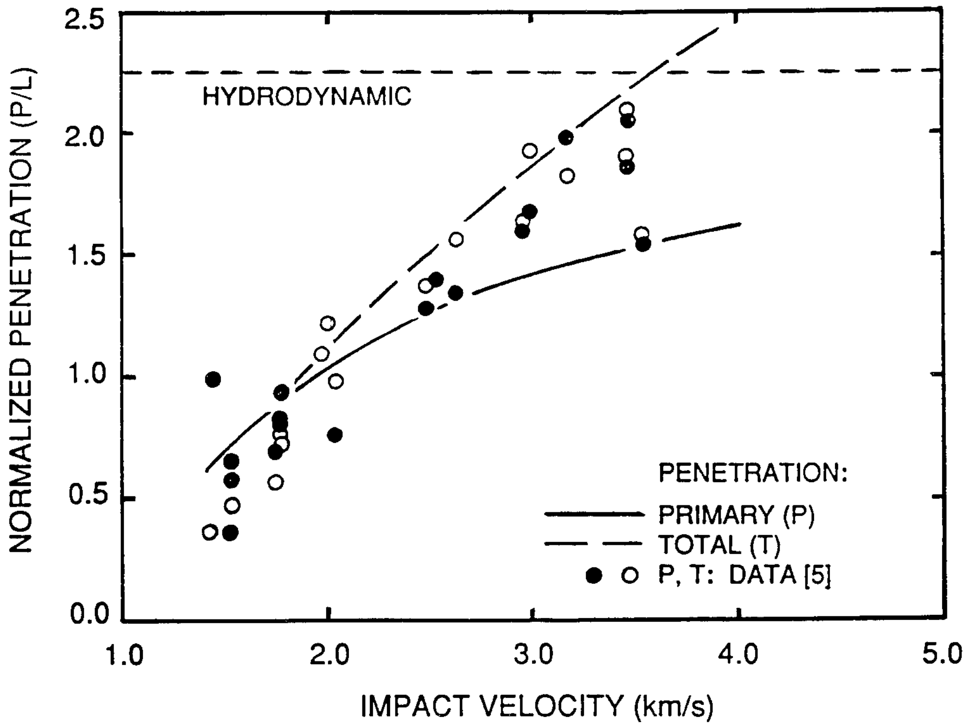

Figure 6. Calculated and experimental primary and total penetration in Al_2O_3.

Calculated results for the aluminum metal target are shown in Figure 7. In this case, the penetration analysis was applied, of course, without the time-dependent damage mechanism. As can be seen, the penetration theory represented the experimental data for primary penetration behavior reasonably well across the wide range of velocities considered. The penetration depths above the hydrodynamic limit for impact velocities from 2,500 m/s to 5,000 m/s are the classic result when rod strength exceeds that of the target. This result and previous results [6] for tungsten alloy and steel rods against steel armors suggest that good engineering estimates can be obtained from the penetration integral of equation (1) and the associated equations (2)–(4).

Calculations for primary penetration in AlN targets, together with similar experimental trends in B_4C and SiC [14], suggest that the time-dependent damage model combined with the penetration integral in equation (1) provides the general response of ceramic targets to tungsten rod penetrators. The reason for different behavior by Al_2O_3 ceramic is presently not known.

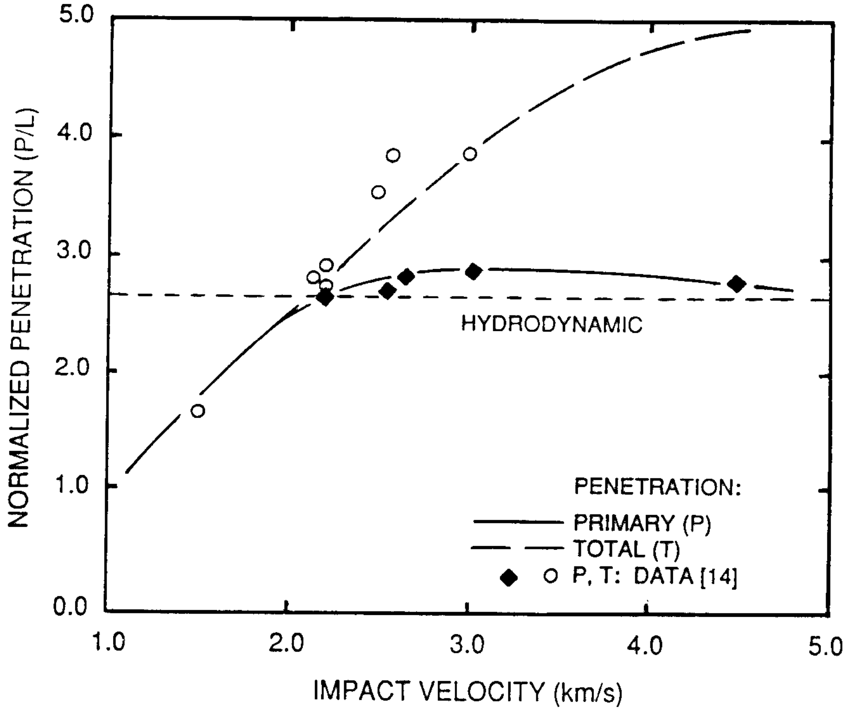

Figure 7. Calculated and experimental primary and total penetration in aluminum.

5.2 Penetration by Rod Erosion Products. The additional penetration observed in Figures 5 and 7 for AlN and aluminum, and that reported for B_4C and SiC [14], cannot be explained in terms of ordinary penetration by the initial tungsten rod. Secondary penetration calculations for the rod erosion products are included also in Figures 5 and 7, where total penetration is the sum of primary and secondary calculated penetration. In these cases, the calculations naturally give rise to a certain impact velocity, where secondary penetration first can be observed. This threshold condition appears at an impact velocity of about 1,800 m/s for the AlN target and 2,100 m/s for the aluminum target. In that regard, there is good agreement between experimental data and calculated results. Further, calculations for total penetration show a near-linear penetration response in the region about the threshold velocity which is consistent with the data reported by Orphal et al. [4] and Orphal [14].

There is an implication that if the REP integrity as a penetrator can be maintained, then total penetration could be expected to reach a new limit beyond the customary hydrodynamic limit. Those limits are estimated to be somewhere near P/L = 3.5 for AlN at an impact velocity of 6,000 m/s and P/L = 5 for aluminum at an impact velocity of 5,000 m/s. While the analysis

possibly explains the large total penetration observed through impact velocities included in the data sets, it is not clear that such high P/L values can actually be obtained.

Calculations for total penetration in Al_2O_3 ceramic, as shown in Figure 6, along with those for primary penetration appear to bracket the data at high impact velocity. However, there does not appear to be an established pattern in the data with regard to any threshold condition or any significant difference between primary and total penetration depths. There is also somewhat more variation in the data, which makes the analysis difficult. The data suggest that Al_2O_3 ceramic does not follow the same trend as other materials examined, but the differences in responses are not understood. However, it is believed that the very deep penetrations reported can only occur under conditions where the ceramic strength has been degraded significantly and perhaps additional effects, yet to be identified, are present.

6. SUMMARY AND CONCLUSIONS

The analyses conducted in this study provide several interpretations for the experimental observations of pure tungsten rods penetrating low-density materials. One result confirms that the constant or near constant penetration rates observed are a consequence of the high impact velocities considered (above 2,000 m/s) in combination with target materials that have low initial strength (aluminum) or those whose initial strength is high but reduced during the penetration process (ceramic). Targets with low strength will tend toward hydrodynamic penetration rates while those with initially high strength will have a significantly lower penetration rate. For target materials with initially high strength that become comminuted during penetration, the penetration process becomes governed by friction. The dynamics of this condition suggest a real possibility that penetration depths may never reach hydrodynamic levels, even at very high impact velocities. Thus, it follows that primary penetration in many ceramics will necessarily be less than hydrodynamic levels.

Penetration by rod erosion products was explored as a possible explanation for additional and very high penetrations observed in the ceramics and also aluminum. The analysis provided mass and velocity distributions for the erosion products and these served as a basis for estimating additional or secondary penetration possibilities. Results were obtained for rod-like behavior by

the erosion products. Under such conditions, the analysis provided results that were in very good agreement with three features of the experimental data for AlN ceramic and aluminum target materials. These features included the onset of secondary penetration at an impact velocity of about 2,000 m/s by the initial rod, a near linear increase in total penetration over an impact velocity range of from 2,000 m/s to 4,000 m/s, and reasonable values for the magnitudes of secondary penetration. The analysis bounded the experimental results for Al_2O_3 at high velocity but was unable to explain differences in its behavior relative to the other materials.

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ATTN: AMSRL-WM-TC
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13. ABSTRACT ***(Maximum 200 words)***

This paper presents an analysis of recently reported experimental data on penetration of semi-infinite ceramic and metal targets by long rods at relatively high velocity (up to 4,500 m/s). Data examined were for pure tungsten rods having length-to-diameter ratios of 15 and 20. The rods were impacted by confined aluminum nitride (A1N), alumina ($A1_2O_3$), and a metal target of aluminum in reverse ballistic tests. Penetration rates were reported to be essentially constant throughout the penetration process at all impact velocities considered. Further, depths of penetration characterized as "primary penetration" agreed with expected levels based on measured penetration rates and rod erosion rates. However, above an impact velocity of about 2,000 m/s, considerably more penetration was observed in A1N and aluminum targets. In this effort, established techniques were used to treat penetration into semi-infinite ceramic, to include the high initial strength of the ceramic and its degradation, in time, through time-dependent damage mechanisms. The model results agreed with reported primary penetrations for A1N and aluminum targets. Further, additional "secondary penetration" by the rod erosion products at these high impact velocities was explored. This report includes detailed descriptions of the analysis and some physical interpretations for the observations. This research was based on U.S. Government-sponsored work and open literature sources.

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